

MAY 17 1959 RECEIVED

(For presentation at the 3rd.
National Conference on Heat Transfer)

PREREQUISITES FOR A MODEL OF NUCLEATE BOILING

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INTRODUCTION

For over 30 years boiling heat transfer has been recognized as an attractive way to achieve cooling rates, which may be up to a magnitude greater than convective rates. At first, the heat-transfer technology did not offer any reliable means for designing equipment to utilize the boiling phenomenon. Poor design could cause the equipment to operate in the "film boiling" regime with rather disastrous burnout conditions. Furthermore, the heat-flux requirements for most equipment did not reach beyond the convective regime, so there were no great demands to operate at a risky boiling condition.

With the introduction of nuclear energy and the advances in the chemical rocket, a new demand for substantially higher cooling rates has stimulated interest in boiling heat transfer and, incidentally, in other schemes of heat transfer. One only has to look at the recent heat transfer literature to be aware of this movement. For the boiling heat-transfer phenomena, the heat-transfer mechanism apparently has not been pinned down, even though many authors claim to have found the particular correlation or model to design heat-transfer equipment for nucleate boiling.

A comparison of the literature reveals that there is considerable variance in the model describing the mechanism and in the methods of correlation. While data are presented to verify models or correlations, the

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data generally involve limited regimes of boiling conditions. Generally the correlation can be catalogued into three types. First, there are correlations that employ the dimensionless parameters of convective heat transfer such as Nusselt number, Prandtl number, and so on. By a sort of brute force method, data are fitted to these dimensionless relationships. The second correlation method involves a fresher approach to the problem. A model of the bubble-ebullition process and the heat transport attributable to the bubble motion is postulated. The correlation is based upon equations describing the motion and energy relations as they pertain to the model. There is even disagreement in the models postulated for this category of correlations. The third correlation method is really a combination of the first two. The model is substantially the same as the bubble-ebullition model but in correlating the heat-transfer data, dimensionless parameters of convective heat transfer are employed, which generally requires a redefinition of such parameters as Reynolds number and Nusselt number.

The purpose of this paper is to compare the models and correlations of nucleate boiling that have appeared in the recent literature. From such a comparison and with the aid of boiling data from published and unpublished sources, the prerequisites for a model of the boiling heat-transfer mechanism will be presented. The unpublished data were obtained experimentally by the authors.

LITERATURE SURVEY

Dimensionless Parameter Correlations

The usual methods of presenting convective heat-transfer data, such as the log-log plots of Nusselt-Prandtl group and Reynolds number or the Colburn j factor and the Reynolds number plot, do give relationships among these parameters for boiling heat transfer. In figure 1, nucleate boiling and convective data for water obtained from an electrically heated tube are shown. While the convective correlation can be applied quite generally, the boiling correlation (if it can be called that) is restricted to the geometry and the conditions of the tube. Such a correlation method is probably quite useful when it pertains directly to a specific piece of heat-transfer equipment. The designer can "hold" the operation to the nucleate regime by consulting such a correlation. However, the complexity of the boiling mechanism prohibits the designer from pulling out from the correlation generalized relationships between the wall temperature, the bulk temperature, and the heat-transfer coefficient that apply to any nucleate boiling heat-transfer problem.

Several methods have been proposed to generalize the dimensionless convective heat-transfer correlations for boiling heat transfer. Gilmour (1)¹ suggests formulating the Reynolds number from a mass velocity of the vapor. This mass velocity G is simply the vapor rate per unit surface area multiplied by the ratio of the liquid to the vapor density. Gilmour also introduced a dimensionless term to account for the effect of pressure on the boiling mechanism. The correlation equation is

¹Numbers in parentheses indicate references at end of paper.

$$\left(\frac{h}{cG}\right)\left(\frac{c\mu}{k}\right)^{0.6}\left(\frac{\rho_l\sigma}{P^2}\right)^{0.425} = \frac{0.001}{\left(\frac{DG}{\mu}\right)^{0.3}}$$

where

h	local heat transfer coefficient
c	specific heat at constant pressure
$G = \frac{V}{A} \frac{\rho_l}{\rho_v}$	mass flow velocity of vapor
μ	viscosity
k	thermal conductivity
ρ_l	density of liquid
ρ_v	density of vapor
σ	surface tension
P	pressure
D	diameter
V/A	vapor rate per unit surface area

Boiling data for a number of fluids were correlated in this fashion. It is interesting that the application of this correlation requires knowledge of the rate of vapor production per unit area. This type of data is not easy to obtain even in a heat-transfer apparatus.

Mumm (2) studied the effects of heat flux, pressure, flow rate, and quality on heat transfer in a channel with a steam-water mixture. He found that the local heat-transfer coefficient increases up to a quality of about 50 percent and then decreases toward the gas film coefficient at a quality of approximately 70 percent, where burnout occurred. Mumm used dimensional analysis to correlate his data, which yielded the following equation:

$$\frac{h D_e}{k_f} = \left[4.3 + 5.0 \times 10^{-4} \left(\frac{V_{fg}}{V_f} \right)^{1.64} x \right] \left[\left(\frac{q''}{G h_{fg}} \right)^{0.464} \left(\frac{D_e G}{\mu_f} \right)^{0.808} \right]$$

where

- h boiling heat transfer coefficient
- D_e equivalent diameter
- V_f specific volume of liquid
- V_{fg} specific volume change in evaporation
- x fraction of flow evaporated
- k_f thermal conductivity of fluid
- q'' heat flux
- h_{fg} latent heat of vaporization
- G mass flow
- μ_f absolute viscosity of fluid

Similar dimensionless correlations appear in the earlier literature. While they may be useful in many specific engineering applications, they are not descriptive of a boiling mechanism and they cannot be applied broadly to many boiling heat-transfer problems.

THE BUBBLE EBULLITION MODELS

It is generally recognized that the mechanism of boiling heat transfer is appreciably different from that of convective heat transfer. Consequently, the approach of many researchers has been to postulate a model describing the boiling phenomenon and to formulate mathematical relations which describe the behavior of the model.

All of these models presume a mechanism for growth of the vapor bubbles and presume assumptions concerning the role of the bubble in transporting heat. Table I is an attempt to summarize the salient points of a number of these models. Differences in the models and their assumptions will be apparent in an inspection of table I. The assumptions pertaining to Gilmour's correlation (1) are included in the table for comparison purposes. In addition to this table, a summary discussion of each of the boiling heat-transfer models will be presented now.

The model used by Levy (3) is quite similar to that employed by Forster and Zuber (4) in some earlier pool boiling work. A film of liquid superheat is assumed to exist along the heated surface and the bubbles are developed in this film. Levy assumes that all the heat transferred from the surface is carried by the bubble in the form of latent heat. From this assumption, he proceeds to develop an expression for q/A , which includes the equation of bubble growth,

$$\frac{Q}{A} = \frac{k_L C_L \rho_L^2}{\sigma T_s (\rho_L - \rho_v)} \frac{1}{\beta_L} (\Delta T)^3$$

where

Q/A heat transfer rate per unit area

k_L thermal conductivity of liquid

C_L specific heat of liquid

T_s saturation temperature

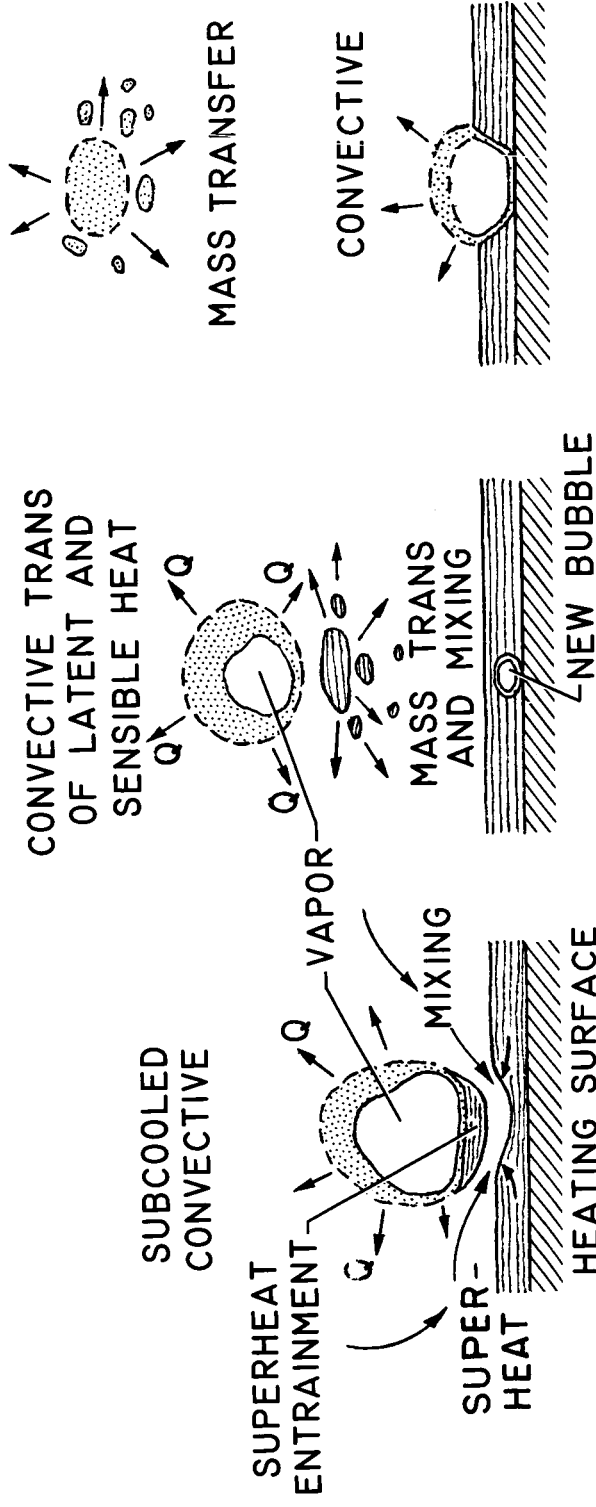
σ surface tension

ρ_L density of liquid
 ρ_V density of vapor
 ΔT wall temperature - saturation temperature
 β_L dimensionless parameter

The dimensionless parameter β_L is related to the geometry of the bubble but was found, through correlations, to be a function of the vapor density and the heat of vaporization of the fluid.

With this kind of correlation, Levy has neglected the effect of fluid stream velocity on the boiling heat transfer. In the paper (3), he applies the correlation to subcooled nucleate boiling and even to burnout conditions.

Bankoff and Mikesell (5) postulated a model based on the Rayleigh equation (6) for bubble growth. However, they differed with other contributors such as Forster and Zuber (4) in assuming that the inertial effects are more important than the conduction effects in controlling bubble growth and collapse. In solving the Rayleigh equation they also neglected surface tension (7). Good agreement exists between experimental rate of bubble growth and collapse and the solution of the Rayleigh equation. The growth and collapse rate curves were symmetrical and steep in slope for either a high degree of liquid subcooling or for high velocities. To the authors this indicated rapid heat transfer from the bubble wall in the subcooled liquid, which justified an assumption of a convection heat-transfer coefficient from the bubble wall. The heat-transfer coefficient was assumed to be a function of the free-stream velocity and bubble radius.



1. BUBBLE LEAVES SUPER HEAT, ENTRAINS SOME SUPERHEAT. TURBULENT MIX OF SUBCOOLED AND SUPERHEAT OCCURS. BUBBLE TRANSFERS HEAT TO SUBCOOLED AND EXPERIENCES CONDENSING.
2. ENTRAINED SUPERHEAT MIXES WITH SUBCOOLED. BUBBLE TRANSFERS HEAT AND CONDENSES. NEW BUBBLE STARTS.
3. BUBBLE COLLAPSES AND MIXES. NEW BUBBLE GROWS THROUGH SUPERHEAT LAYER. BUBBLE EBULLITION AND ATTENDANT HEAT TRANSFER PROCESSES REPEAT CYCLE.

Fig. 3. - Diagram of boiling heat transfer mechanisms.

The numerical answers produced by this model agreed qualitatively with experimental data.

The authors observed that if the condensing rates at the cooled surface of the bubble are large in comparison with the rate of depletion or accumulation of vapor within the bubble, the latent heat transport to the subcooled liquid is not negligible. Referring to some of the boiling heat-transfer data, Bankoff and Mikesell (5) point out that this mode of heat transport may not be negligible.

Still another model of nucleate boiling was devised by Bernath and Begell (8) and like many of these models, it was presented at the 1958 National Conference on Heat Transfer. A superheated film is considered to be adjacent to the heated surface. Bubbles are assumed to form and grow within this film. As the bubbles leave the film to travel into the subcooled turbulent core, the bubble displacement volume is replaced by subcooled liquid flowing from the core.

In addition, the authors assumed that the condensation of the bubbles always occurred outside the film and that the film thickness was sensitive to the free-stream velocity and subcooling. They presented experimental evidence to show that the latter assumption was valid. Appreciable changes in the heat flux were noted for velocities above 6 feet per second. Below this value, velocity appeared to have little or no effect on heat transfer, nor did subcooling have much influence.

Bernath and Begell correlated the boiling heat transfer in two separate empirical relations among saturation temperature, heat flux, and velocity and among subcooling temperature, heat flux, and velocity.

Bubble Ebullition Model - Dimensionless Parameter Correlation

Forster and Greif (9) have described the mechanism of nucleate boiling heat transfer in terms of a "vapor-liquid exchange" model. During bubble growth, in a superheat layer, the bubble pushes a quantity of hot liquid from the heating surface out to the subcooled liquid. The volume of liquid that takes part in this mass exchange is at least as large as the volume of the bubbles formed. The quantity of heat transported by this mechanism is 50 to 250 times as great as the transport of the latent heat of the bubble vapor.

The correlation of boiling heat transfer is based upon the selection of three dimensionless parameters. The Prandtl number to the 1/3 power is arbitrarily selected as the first parameter. The second parameter involves viscosity and an approximation to bubble growth based on Rayleigh's equation (6). The third parameter is a Nusselt number using the radius of the critical bubble ($R_c = 2\sigma/\Delta p$) as the characteristic length. These parameters are presented in two correlation forms, one of which is less sensitive to different liquid properties than the other. This correlation is of the form

$$\frac{q}{h_{fg} a_v} \left(\frac{2\sigma}{a\Delta p} \right)^{1/2} \left(\frac{\rho_L}{\Delta p} \right)^{1/4} = C \left(\frac{\rho_L}{\mu} A^2 \right)^n \left(\frac{\mu c}{k} \right)^{1/3}$$

where

a thermal diffusivity

n arbitrary exponent

h_{fg} latent heat of vaporization

σ surface tension

ρ_L density of liquid

ρ_v density of vapor

c specific heat at constant pressure

k thermal conductivity

q heat flux

C constant

R_c critical bubble radius

Δp pressure difference

A coefficient of bubble growth $\left[A = \frac{c\rho_L T_s \sqrt{\pi a}}{(h_{fg}\rho_v)^2 J} \right]$

T_s saturation temperature

J mechanical heat equivalent

In addition to this correlation and boiling heat-transfer model, Forster and Greif make several conclusive statements about the nature of boiling heat transfer: First, pool boiling data can be applied to boiling phenomenon of fluids in motion, or fluid velocity has little effect on boiling heat-transfer rates. Second, boiling heat flux is insensitive to subcooling. More discussion will be devoted to these conclusions later.

Rohsenow (10) presented a similar correlation in the earlier literature. It was radically different from the correlation of reference 9 in that Rohsenow chose to use the mass velocity of the bubbles rather than the bubble growth rate. He defined the bubble Reynolds number in terms of the critical bubble diameter, the mass velocity of the bubbles, and the viscosity of the liquid. Prandtl number, Nusselt number and the bubble Reynolds number were related empirically.

DISCUSSION OF MODELS AND CORRELATION

From the discussion of various models of boiling heat transfer, it is obvious that there are some interesting points of disagreement. One of the more significant of these controversies involves the assumption concerning the effects of velocity and subcooling on the magnitude of boiling heat transfer. Some authors have neglected these effects while others have considered them important.

Sufficient data is available in the literature to settle the argument. The authors Bankoff and Mikesell (5), Bernath and Begell (8), Motte and Bromley (11), Gambill and Greene (12), and Lowdermilk, Lanzo, and Siegel (13), have shown experimentally that both velocity (above 6 ft/sec) and degree of subcooling influence the heat-transfer mechanism appreciably. Consequently, pool boiling results apparently cannot be applied except where the fluid velocity is low. Thus, any model of nucleate boiling must include the effect of fluid velocity if it is to fit most engineering applications.

Other variations in the boiling heat-transfer mechanism involve the notions as to how the heat is transported. For some models, the latent heat transport is neglected while one reference claims that the bubble vapor carries all the heat that is transferred. A middle-of-the-road point of view was presented by Bankoff and Mikesell (5) when they stipulated that the latent heat transport is small but not insignificant. Jakob (14) (pp. 625 to 629) has shown that the latent heat transport of bubbles does not even approach the magnitude of boiling heat transfer.

The actual mode or modes of heat transfer in the boiling mechanism are difficult to observe experimentally, and thus verification of a model cannot be set forth. However, because of the magnitude of the heat transfer, it seems reasonable to assume some mass transport mechanism. This is essentially what Forster and Greif (9) and Bernath and Begell (8) assumed when they postulated a vapor-liquid exchange mechanism. Still undefined in this mechanism is how the bubble moves a quantity of liquid from the superheated film (adjacent to the heated surface) to the sub-cooled core. Forster and Greif considered the quantity of liquid participating in this mass transport as equivalent in volume to the volume of the bubbles generated.

Proposed Model of Nucleate Boiling Heat Transfer

The model of boiling heat transfer to be proposed can be divided into three principal mechanisms. All of these mechanisms are interrelated, but for purposes of discussion they will be considered separately:

- (a) The bubble-surface convective heat-transfer mechanism
- (b) The mass transport mechanism
- (c) The turbulent exchange mechanism

The following discussion will elucidate each of these mechanisms, which may have several contributing effects. The over-all model is proposed for boiling conditions when the fluid is in motion with respect to the heating surface.

Bubble Surface Convective Heat-Transfer Mechanism

In this over-all model of nucleate heat transfer, the nucleation process and the effect of surface conditions will not be considered. It is recognized that surface conditions are important in the ebullition process (14) and (15), however, it has been found difficult to include these surface effects in any boiling heat-transfer model. For this reason and also because the objective of the proposed model is to explain the role of the bubble in the heat-transfer mechanism, it will be assumed that a bubble has been formed. All experimenters who have proposed bubble models assume that the bubble forms in a region of superheat that exists along the heated surface. Figure 2 is a schematic diagram of the bubble still attached to heating surface. This picture of the bubble shows it absorbing heat from the heated surface and the superheated liquid and then expelling heat to the subcooled liquid. During the process of bubble growth, which occurs while the bubble is attached to the surface, heat is transferred into the bubble through the heating surface and through the bubble surface in contact with the superheat layer.

Considering the heat transfer out of the bubble, it is assumed that the bubble will grow greater in diameter than the thickness of the superheat (15) and thus, it will protrude into the subcooled region. The bubble surface in contact with the subcooled region transfers heat out of the bubble. At least two effects enhance the heat-transfer coefficient for the bubble surface in contact with the subcooled liquid. First, if the fluid is in motion, the fluid velocity over the surface of the bubble produces a forced convection effect. Second, there is considerable

turbulence or circulation within the bubble. Both the condensate and the vapor experience this circulation, which aids the convective heat-transfer process from the bubble interior to the subcooled liquid. The condensate is also one of the chief agents in the mass transport mechanism, which will be discussed further. Ellison (17) has observed the circulation of the condensed phase. Elzinga and Banchero (18) studied the heat transfer between liquid drops and a continuous liquid phase. While this is not the model for a vapor bubble in a liquid continuum, there are similarities. Of significance was their observation that circulation could appreciably increase the heat transfer from a spherical drop to a continuum. Thus in a similar manner, circulation of the condensates within the bubble could help the heat transfer.

Harrison (19) experimentally observed the collapse of bubbles generated in a cavitating Venturi tube. In conjunction with the photographic observation, he made use of a piezoelectric crystal to pick up the pressure pulses from the collapse of the bubbles. For example, a 1 centimeter bubble on collapse generated a 10-atmosphere pulse measured at a distance of 10 centimeters from the bubble. Harrison estimated this pressure pulse to be 4000 atmospheres at the locale of the bubble, which indicates high local velocities in the vicinity of the bubble collapse. Bankoff and Mikesell (5) observed that the bubble-growth curve is a mirror image of the collapse curve. Consequently, during bubble growth it can be argued that large local velocities are present comparable with those observed for the condition of bubble collapse. The induced velocity, which can be thought of as turbulence, helps in the heat transfer from the superheat region into

the bubble. This mechanism alone can explain a part of the augmented heat transfer experienced when convective heat-transfer changes into nucleate boiling heat transfer. Inspection of figure 2 shows that the bubble surface will at least double the local heat-transfer surface area of the heating surface. Even though the heat-transfer coefficient over the surface of the bubble is no larger than the convective coefficient, the increased surface area will increase the heat transfer proportionately. However, it is suspected that the heat-transfer coefficient of the bubble surface is greater than that of the heated surface under purely convective conditions because of turbulence. Turbulence affects the bubble interface heat-transfer rate in at least two ways. First, the liquid surrounding the bubble is highly turbulent and second, the two-phase fluid comprising the bubble is turbulent. More will be said about turbulence later. The significantly higher heat-transfer rates of boiling may be attributed to the increased area and higher heat-transfer coefficient.

The Mass Transport Mechanism

Under favorable stability conditions, the bubble leaves the heating surface and moves into the subcooled liquid. Buoyancy and lift forces (the result of liquid velocity over the bubble) translate the bubble into the subcooled liquid. On leaving the surface the bubble entrains some of the superheated liquid and deposits it in the subcooled layer. The bubble also transports a considerable amount of liquid as condensed vapor and bubble wall. To complete the mass transport, the vapor entrapped in the bubble should be included. The enthalpy of the vapor-liquid mixture is deposited in the subcooled liquid.

The Turbulent Exchange Mechanism

As the bubble leaves the superheat layer some superheated fluid is entrained, as mentioned previously. This mass of superheated fluid is mixed into the subcooled liquid through turbulence. The void that is left in the superheat layer as the bubble leaves is "filled" through a turbulent exchange between the subcooled liquid and the superheat layer. Bubble growth and the motion of the bubbles create highly turbulent conditions, which contribute to the effectiveness of turbulent exchange. Photographic evidence has shown this to be an important mechanism (16)(20).

Evaluation of the Mechanisms

The over-all nucleate boiling heat transfer is a cumulative effect of the mechanisms just discussed. The least important of the three is the mass transport mechanism. Several references have considered this to be a latent heat transport only. But, there could be an appreciable amount of liquid in the bubble, and so the effect of mass transport may be significant. Further experimental evidence is warranted to determine the magnitude of the mass transport especially for conditions of appreciable subcooling. Here, the transport of a hot vapor-liquid mixture into a cold liquid could affect appreciable energy changes in the system.

The turbulent mixing and the convective effects of the bubble surface are the important mechanisms of boiling heat transfer. It would be difficult to single out the most important of these two because they are interrelated. Perhaps the convective heat transfer of the bubble surface is the more important for high fluid velocities. What can be concluded, however, is that the most significant heat-transfer processes go on while

the bubble is attached to the surface or has left the surface but is still in the vicinity of the superheat layer.

The concept of convective heat transfer of the bubble surface accounts for the effects of fluid motion velocity and subcooling on the boiling mechanism. Experimental observation shows that the boiling heat transport is enhanced with high fluid velocities (21). Employing the proposed mechanism as an explanation, the high heat-transfer coefficient can be attributed to high velocities over the bubble contact surface. The increased fluid velocity probably also assists the turbulent mixing process by improving the lift forces on the bubbles.

Subcooling also increases the magnitudes of the heat flux (5) and (20) and permits a greater range of operation in the nucleate boiling regime. The greater heat flux can be attributed to the larger temperature potential between the bubble and the free stream.

In summarizing it appears that a suitable boiling heat-transfer model for dynamic flow conditions should include the three principal mechanisms presented in this paper. The popularly accepted mechanism of turbulent exchange (or liquid-vapor exchange) may be adequate for pool boiling, but it is inadequate when the subcooled liquid is moving at velocities above 6 feet per second. A convective heat-transfer mechanism for the bubble helps to comprehend the effects of subcooling and fluid velocity on the boiling heat transfer.

The mass transport of the bubbles may be a sizeable quantity when the condensates as well as the bubble vapor are considered. Such a mass transport could involve an appreciable heat transport into the subcooled fluid.

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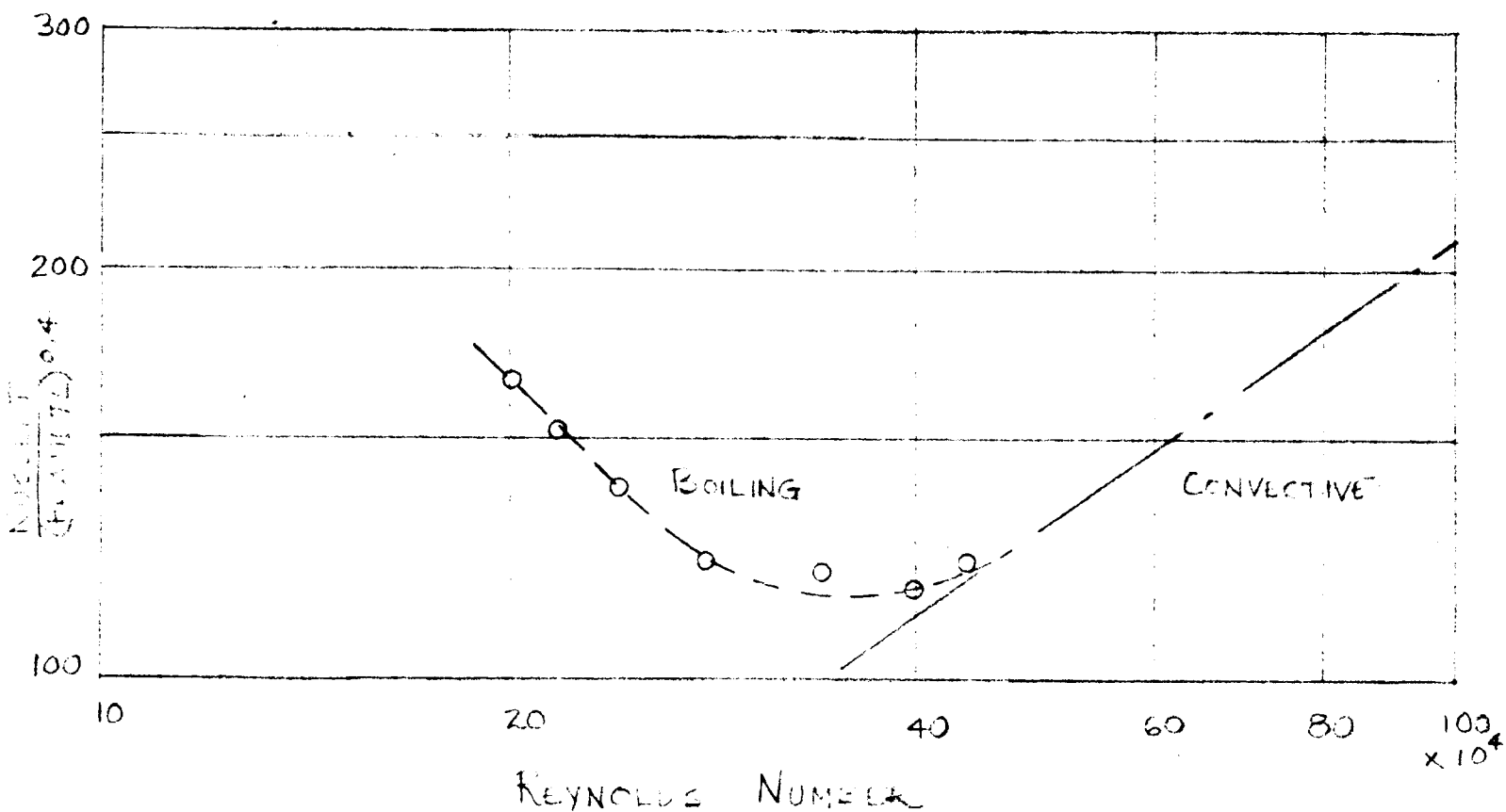
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TABLE I. - SUMMARY OF BOILING HEAT-TRANSFER MODELS

Author of reference	Model of boiling heat transfer	Method of data correlation	Principal assumptions	Experimental results or conclusions
C. Gilmour (1)	Postulates a Re, Pr, Nu correlation based on a pseudo Re number. Re number is based on a mass velocity	Re, Pr, Nu correlation	(1) Assumed exponents on Stanton and Prandtl number to be 1 and 0.6, respectively, in correlating the data (2) The vapor leaving the surface is immediately replaced by cooler liquid	A number of fluids have been used in the correlation successfully
S. Levy (3)	Used Forster-Zuber model of bubble growth. Thin model involves Rayleigh eq. to describe bubble growth	Correlates data for Q/A as a function of the cube of the ΔT , a bubble geometry parameter and other properties of the fluid such as surface tension, and specific heat: $\frac{Q}{A} = \frac{k_C \rho_L^2}{\sigma T_s (\rho_L - \rho_V)} \frac{1}{\beta_L} (\Delta T)^3$	(1) Forster-Zuber assumed no viscosity, no inertia of liquid spherical bubbles, incomp. flow (2) The bubbles are assumed to transport all the heat away from the heat transfer (3) No surface conditions considered (4) Bubble growth is unaffected by fluid velocity (5) Heat rate to bubble is a function of $h_{fg} \rho_V \text{ vol}_{\text{bubble}}$	(1) Found the coefficient β in the correlation to be a function of ρ_V and h_{fg} only (2) Were able to correlate data from Cichella Bonilla and McAdams
Bankoff and Mikesell (5)	Used Rayleighs model for bubble growth in an irrotational liquid. Bubble is generated in superheat layer along surface	Obtain the same growth-collapse curves as Rayleigh eq. for a simpler model	(1) Neglect the surface tension term in Rayleigh eq. (2) Convective turbulent heat transfer controls the heat transfer from the bubble. Heat transfer coefficient is of the form $h \propto \text{Re}^{-0.2}$ (3) The inertial terms dominate the eq. of motion for bubble growth	(1) Boiling heat transfer rates are in substantial agreement with turbulent flow heat transfer rates (2) Subcooling and velocity have an appreciable effect on the collapse rate of bubbles (3) Latent heat transport may be an important mode of heat transport in subcooled liquids
Bernath and Begell (8)	A film is assumed along heated surface. Heat diffuses from the film into turbulent core. Bubble growth takes place within film. Cooler liquid replaces bubble ebullition volume	Empirically related the ΔT_{sat} and ΔT_{sub} as a function of Q/A and velocity	(1) The model specified is really an assumption (2) In addition, the bubbles condense outside the film (3) Film thickness is a function of free-stream turbulence, subcooling and heat flux	(1) Increasing coolant velocity and subcooling reduces the superheat (2) Velocities less than 6 feet per second don't affect the superheat.
Forster and Greif (9)	The model used in the Forster-Zuber model which in turn is founded on the Rayleigh eq. for bubble growth. The mechanism involves pushing the liquid from the surface to the subcooled liquid	The correlation is based on dimensionless parameters. Two of the parameters are really Pr and Nu. The Re number is based on bubble growth and is an outcome of a solution of the Rayleigh eq.	(1) No viscosity, no inertia of liquid bubbles, incomp. flow (2) The chief mechanism of heat trans. is vapor liquid exchange (3) In the nucleate regime there is a point where heat flux and superheat are related by pool boiling data (4) The heat flux in nucleate boiling is insensitive to subcooling or velocity effects	(1) Were able to correlate boiling data for a number of fluids in the nucleate regime using Pr, Nu correlations

FIG 1 CONVECTIVE AND BOILING HEAT TRANSFER DATA
 SHOWING DIMENSIONLESS CORRELATIONS FOR
 1/4 INCH INTERNAL DIAMETER TUBE, 12 INCHES LONG.
 TAP WATER, 30 POUNDS PER SQUARE INCH



BOILING WATER $NU = 1.57 \times 10^6 RE^{-0.975} PR^{0.4}$
 NON BOILING WATER $NU = 0.0781 RE^{0.078} PR^{0.4}$

Subcooled Liquid

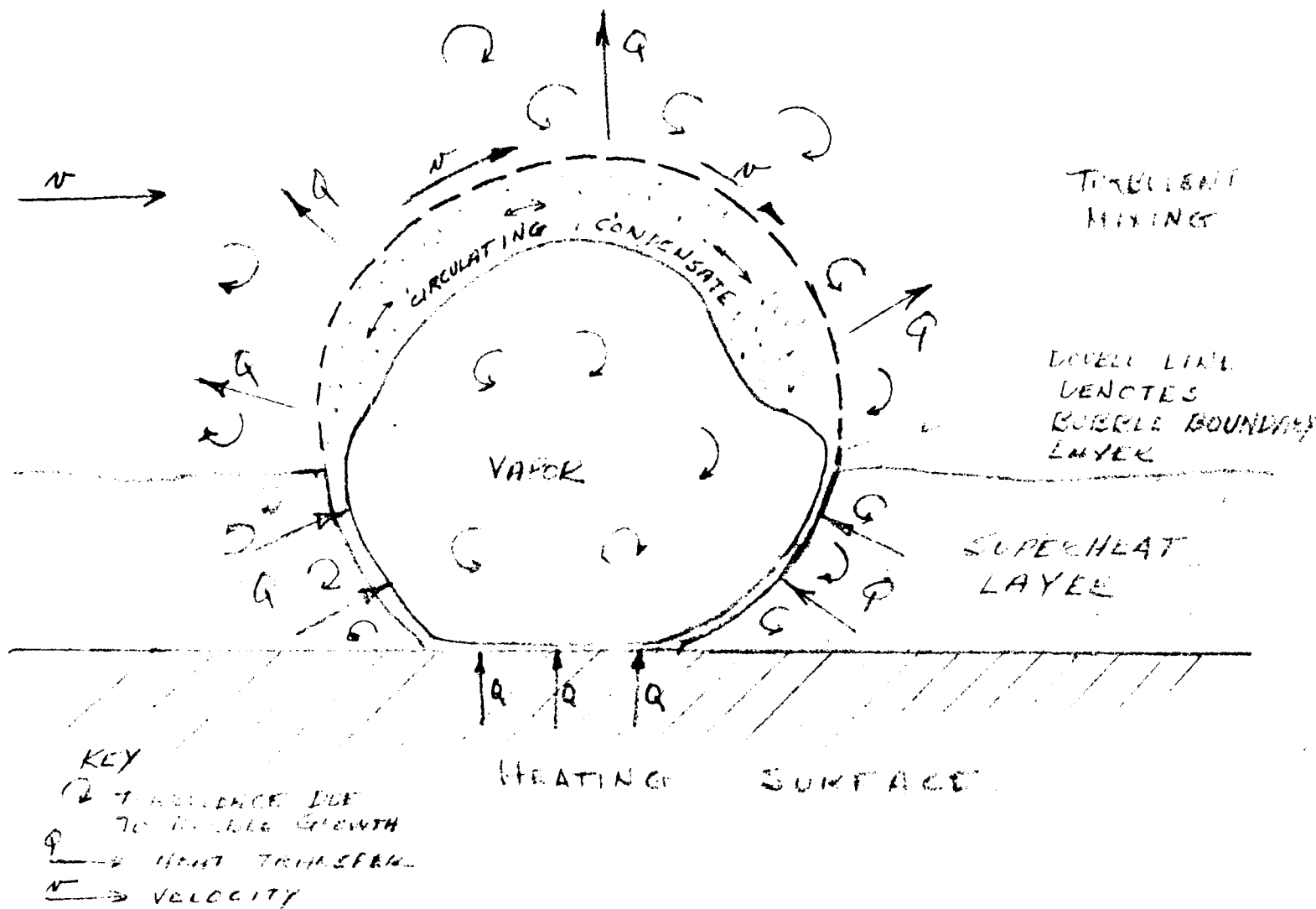
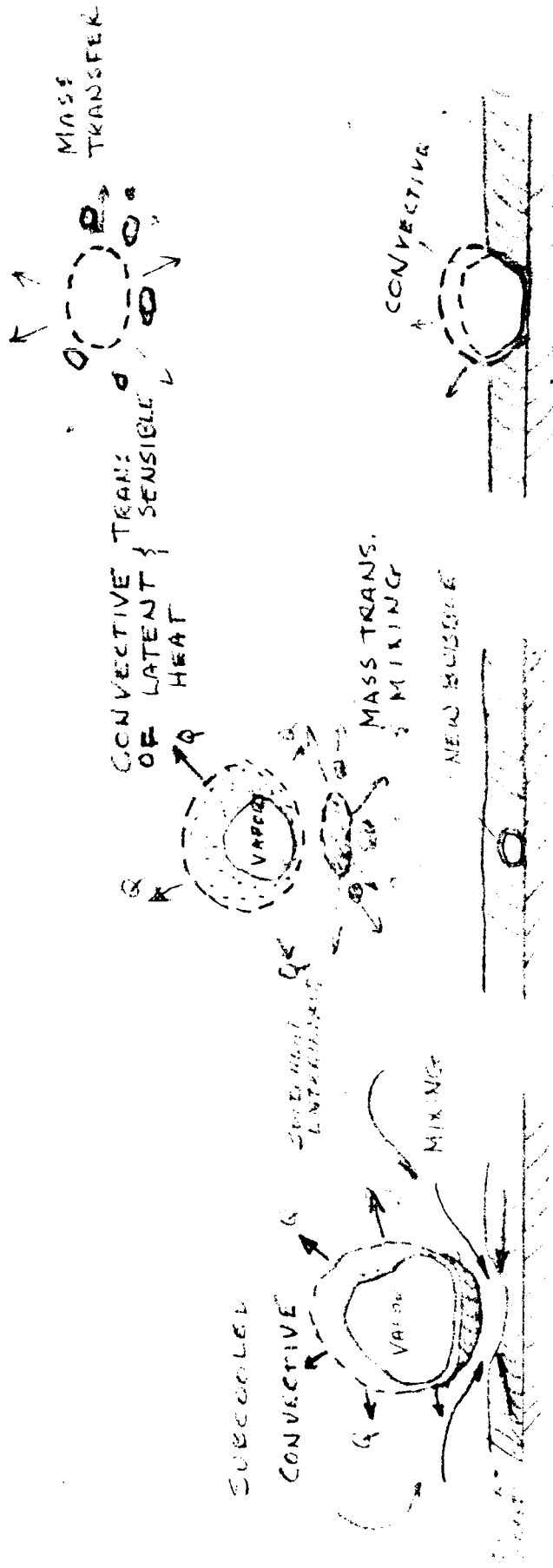


FIG 2. SCHEMATIC OF BUBBLE ATTACHED TO HEATING SURFACE

FIG 3 DIAGRAM OF BOILING HEAT TRANSFER MECHANISMS



① BUBBLE LEAVES SURF - HEAT, ENTRAINS SOME SUPERHEAT. TURBULENT MIX OF SUBCOOLED LIQ & SUPERHEAT OCCURS. BUBBLE TRANSFERS HEAT TO SUBCOOLED LIQ & EXPERIENCES CONDENSATION.

② ENTRAINED SUPERHEAT MIXES WITH SUBCOOLED LIQ. BUBBLE TRANSFERS HEAT & CONDENSES. NEW BUBBLE STARTS.

③ BUBBLE COLLAPSES & MIXES. NEW BUBBLE GROWS THROUGH SUPERHEAT LAYER. BUBBLE ENJOINS LATENT HEAT TRANSFER. PROCESSES REPEAT CYCLE.

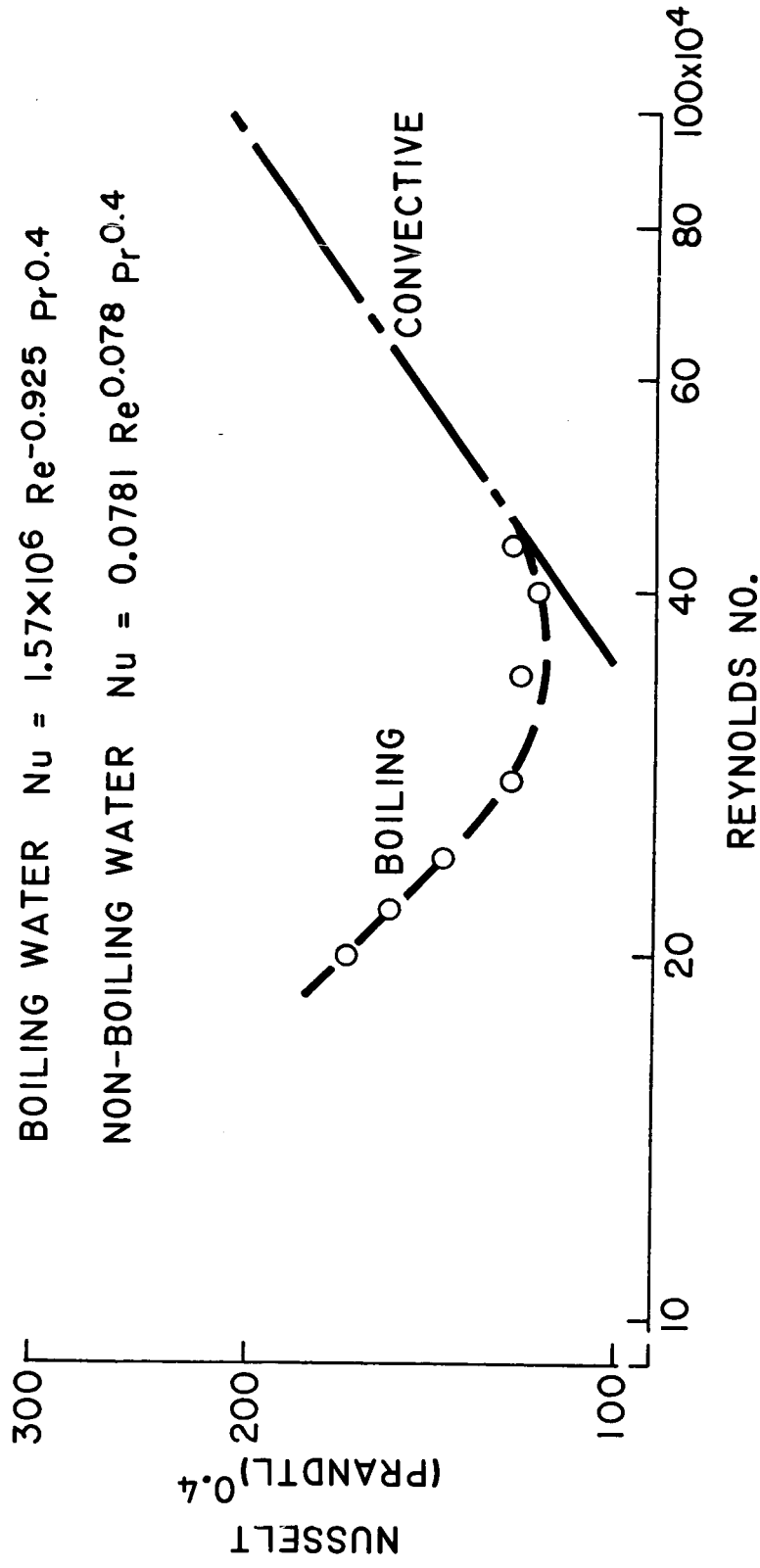


Fig. 1. - Convective and boiling heat transfer data showing dimensionless correlations for 1/4 inch internal diameter tube, 12 inches long. Tap water, 30 pounds per square inch.

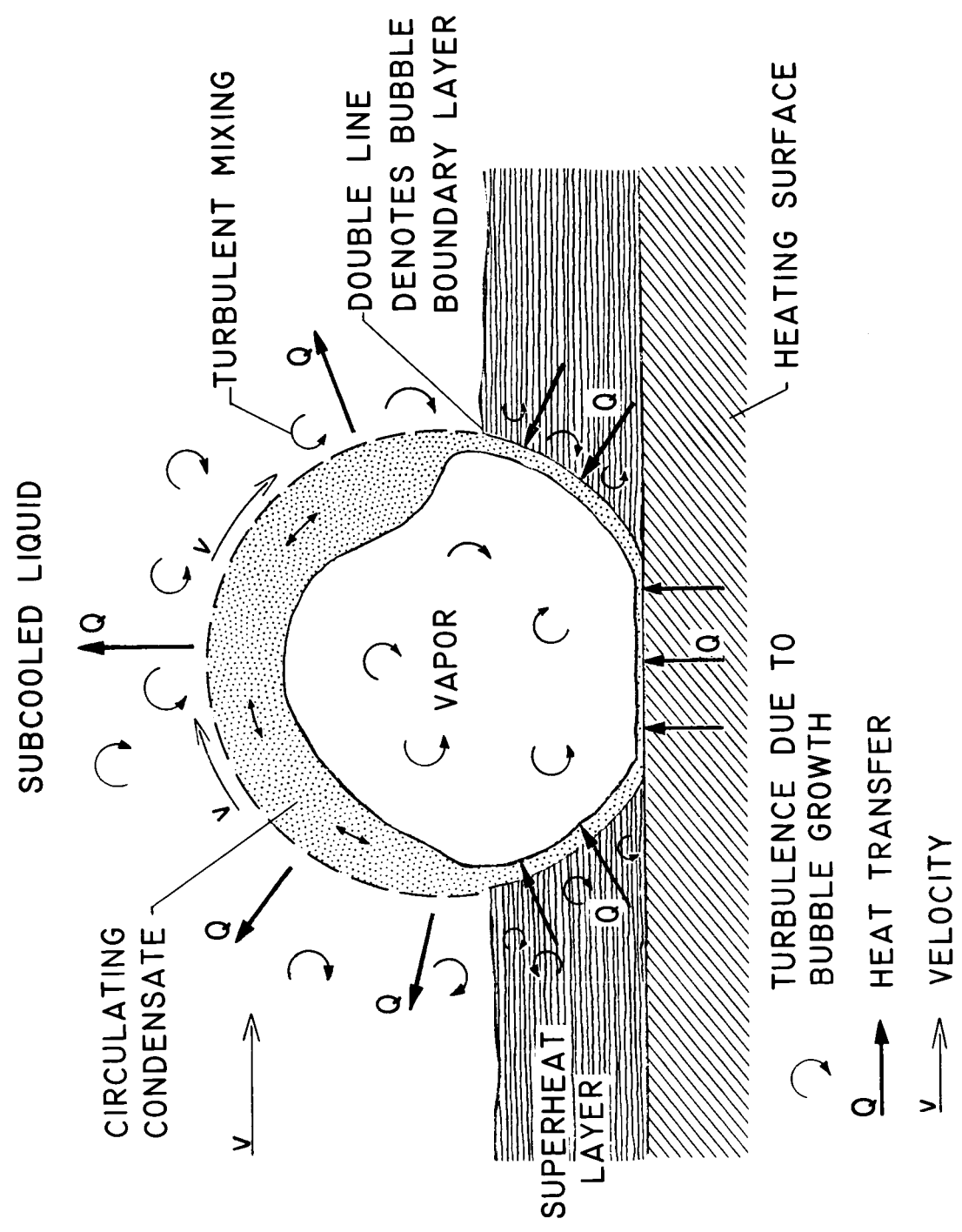


Fig. 2. - Schematic of bubble attached to heating surface.